# Is there a detachment beneath the Taiwan thrust belt? A view from seismic energy release

## ¿Hay un despegue bajo el cinturón orogénico de Taiwan? Una visión proporcionada por la energía sísmica liberada

**D. Brown[1], M. Schimmel[1], J. Alvarez-Marron[1], G. Camanni[1] and Y.-M. Wu[2]**

1 Instituto de Ciencias de la Tierra "Jaume Almera", CSIC, Barcelona, Spain
2 Department of Geosciences, National Taiwan University, Taipei, 106, Taiwan

**Abstract:** The Taiwan thrust belt has generally been presented as being wedge-shaped, with a gently east-dipping, shallow basal detachment that extends from the frontal thrust to the eastern part of the Central Range. More recently, with a growing amount of precisely located, high-quality earthquake data indicating that much of the crust beneath the Taiwan thrust belt is seismically active, this model has come into question. Here we present an imaging technique based on cumulative seismic energy release to illuminate the deep structure beneath the Taiwan thrust belt. This data corroborates the previous interpretations of a shallow detachment beneath the Western Foothills, but it also indicates that this detachment does not continue eastward beneath the more internal ranges. We suggest that a model in which the Western Foothills and the Hsuehshan Range is a zone of transpression that involves nearly the entire crust better fits the available data. In this model, the Western Foothills detachment ramps down into the lower crust along the western flank of the Hsuehshan Range and is truncated by the Lishan fault. This implies that there is no structural linkage between the Hsuehshan and Central ranges and that there is no material transfer across the Lishan fault.

**Key words:** Taiwan, trust belt, detachment, seismic energy release.

***Resumen**: La cordillera de cabalgamientos y pliegues de Taiwan se ha descrito generalmente con una forma de cuña, con un despegue basal que se inclina suavemente al este y que se extiende desde el cabalgamiento frontal hasta la parte oriental de la Central Range. Recientemente, con el aumento de datos de terremotos de alta calidad y localizados con precisión y que indican la existencia de sismicidad en gran parte de la corteza, el modelo de la cuña se ha puesto en cuestión. Aquí presentamos una técnica de iluminación de la estructura profunda en la cordillera de Taiwan basada en el cálculo de la energía sísmica acumulada liberada. Estos datos corroboran las interpretaciones previas de un despegue basal bajo la Western Foothills pero también indican que este despegue no continúa hacia el este bajo las zonas más internas. Nosotros sugerimos que un modelo en que la Western Foothills y la Hsuehshan Range constituyen una zona de transpresión que involucra a casi toda la corteza se acomoda mejor a los datos. En este modelo, el despegue en la Western Foothills profundiza mediante una rampa hasta la corteza inferior a lo largo del flanco occidental de la Hsuehshan Range y es truncado por la Falla de Lishan. Esta interpretación implica que no existe conexión estructural entre la Hsuehshan Range y la Central Range y que no hay transferencia de material a través de la Falla de Lishan.*

***Palabras clave**: Taiwan, cordillera de cabalgamientos, despegue, energía sísmica liberada.*

## INTRODUCTION

One of the basic tenets in the geometric, mechanical, numerical, and analog modeling of mountain belts is that there is a through-going, gently dipping basal detachment at shallow depths beneath their flanks, above which a foreland thrust and fold belt develops. The Taiwan mountain belt is often cited as an example *par excellence* of this sort of thrust and fold belt (Suppe, 1980, 1981; Carena et al., 2002), and it has consequently served as an important example for the development of the critical wedge model (Davis et al., 1983; Dahlen et al., 1984). But, does this through-going detachment model indeed apply to the Taiwan thrust belt?

The Taiwan thrust belt has been forming since the Late Miocene as the result of the collision of the Luzon arc with the southeast Eurasian margin. In the surface geology, the Taiwan orogen can be divided into four N-S oriented tectonostratigraphic zones that are separated by major faults. From west to east these zones are; the Western Foothills, the Hsuehshan Range, the Central Range, and the Coastal Range. The Western Foothills, Hsuehshan Range, and the Central Range are comprised of the rocks from the imbricated continental margin of Eurasia and the foreland basin. It is these three zones, and the structures that mark the boundaries between them, in particular the Shuili-Keng and Lishan faults, that are of interest to this paper. The Coastal Range is comprised of volcanic rocks and sediments of the Luzon arc, which is being thrust over the Eurasian margin along the Longitudinal Valley Fault.

By far, the bulk of the data for constructing the structural architecture of the Taiwan thrust belt, including its basal detachment, has come from surface geological observations and shallow reflection seismic data along the western flank of the thrust belt. On a geometric basis for geological cross-section construction, the shallow basal detachment determined from there was then extrapolated eastward beneath the whole thrust belt. Recently, selective picking of relocated earthquake hypocenter data has been presented as a validation of the shallow detachment model (Carena et al., 2002). Nevertheless, with a growing amount of seismicity data indicating widespread activity in the middle and lower crust, particularly beneath the central part of the thrust belt, researchers have begun to challenge the shallow detachment model (Wu et al., 1997, 2004). These authors suggest that any model for the structural architecture of the Taiwan thrust belt needs to incorporate nearly the entire crust and include a number of steeply dipping faults that penetrate to the lower crust, where they possibly link with a deep detachment. This interpretation has significant implications for the geometrical, mechanical and kinematic evolution of the thrust belt that is different from what has so far been predicted by the wedge-shaped shallow detachment model.

Here we present an imaging approach that uses cumulative seismic energy release data to resolve the crustal-scale structure in central Taiwan (Figure 1). By using this approach we are able to determine the locations of the major structures at depth beneath much of the Taiwan thrust belt. We show that a model in which the deep crust of Taiwan is being deformed may be more appropriate than the shallow detachment model.

## SEISMIC ENERGY RELEASE APPROACH

Earthquake hypocenter maps and sections with a large number of seismic events can provide important information about the geometry of fault systems. There are, however, several disadvantages. For example, clustering of events may be misleading in the visual inspection of these maps and sections, since small magnitude events cannot be distinguished from large ones. With an energy increase of about a factor of 30 for each unit increase in magnitude, the cumulative energy released by many small events may not reach the energy of a single large event, and this can mask the important structures along which major earthquakes occur. Also, in hypocenter cross-sections events are generally projected over distances of 10's of km's onto the plane of section. Many of these events may be related to structures that are not present in the plane of the section, or which intersect it in a completely different place from where the events are projected. The advantages of using the cumulative energy release method are that zones of high magnitude earthquakes are readily distinguished and imaged *in-situ*. Following this, we assume that the highs in cumulative energy release are related to earthquakes taking place along the major structures. A limitation of the cumulative energy release modeling is the recurrence time of earthquakes, which can significantly bias the results locally and may account for areas of low energy release such as in the western part of the Central Range. Nevertheless, the large number of events recorded in the study area over the 15 year period used here provides an important new view of the crustal structure.

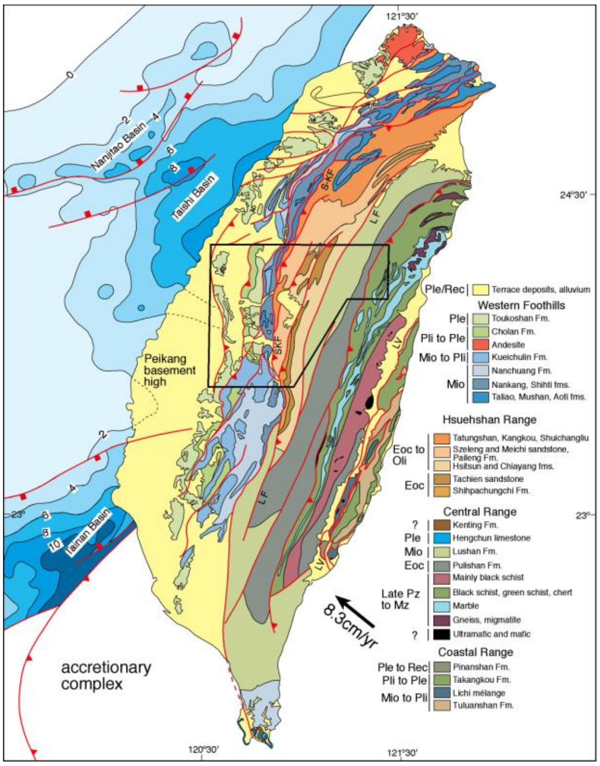


FIGURE 1. *Geological map of Taiwan. The location of the Peikang basement high is shown. SKF = Shuilikeng fault, LF = Lishan fault, LV = Longtudinal Valley.*

For our modeling in central Taiwan (Figure 1), we extracted 34,818 events (>$M_L$ = 2) from the 1991 to 2008 database of relocated earthquakes. In accordance with the Taiwan Central Weather Bureau Seismic Network Earthquake Catalogue, the local magnitude $M_L$ is used to compute the seismic energy release (E, units are in ergs) for each event using the empirical relation

$$\log E = 9.4 + 2.14\ M_L - 0.054\ M_L{}^{**}2$$

In this study, cumulative seismic energy release was determined in a 3D volume using a discretized 100m grid in which the energy is summed for all events that are located within a sphere of 2 km diameter centered at each grid point. Horizontal and vertical slices were then cut through the volume.

## SEISMIC ENERGY RELEASE IN CENTRAL TAIWAN

The seismic energy being released by earthquakes in the Western Foothills of central Taiwan is largely scattered throughout the upper 30 km of crust, with minor amounts being released to a depth of at least 40 km (Figure 2). There is a relatively higher amount of energy being released along its eastern flank, and a marked high occurs in the central and southern part of the map area that is centered at about 10 km depth. The subhorizontal cumulative energy release high located at ca. 10 km depth beneath the Western Foothills can be interpreted to image a basal detachment. This detachment coincides with the one that has been inferred from earthquake hypocenter locations, but is several kilometers deeper than that determined from geological cross-section balancing techniques. The relative increase in cumulative energy release in the upper 10 km of crust along the eastern flank of the Western Foothills seems to be related to earthquakes occuring along faults within the zone.

There is an abrupt deepening in the zone of cumulative energy release beneath the Hsuehshan Range that reaches a depth of ca. 30 km. Along its western flank, there is a steeply eastward dipping zone of high energy release that projects to the surface at the location of the Shuilikeng fault. Along its eastern flank, a steeply westward dipping to vertical truncation of energy release projects to the surface at the location of the Lishan fault. This zone coincides very well with the area of high conductivity imaged by Bertrand et al. (2009). In the southeastern part of the map area, from ca. 20 to 35 km depth, there is a near vertical high in the cumulative energy release that projects to the Lishan fault at the surface. The high energy release in the central part of the Hsuehshan Range range is likely due to faults that have been mapped within it.

In the western part of the Central Range, the seismic energy release is relatively low and is scattered throughout the crust to a depth of at least 40 km. With the present dataset we are unable to determine any relationship between cumulative seismic energy release and geological structures in the western part of the Central Range. Eastward, there is an abrupt increase in the amount of energy being released in the upper 20 to 30 km of crust. At the surface, however, the western margin of this high coincides with the location of the Chinma Tunnel fault, a moderately east-dipping thrust that is uplifting Mesozoic and older crystalline basement rocks and placing them on top of Paleogene and younger rocks to the west.

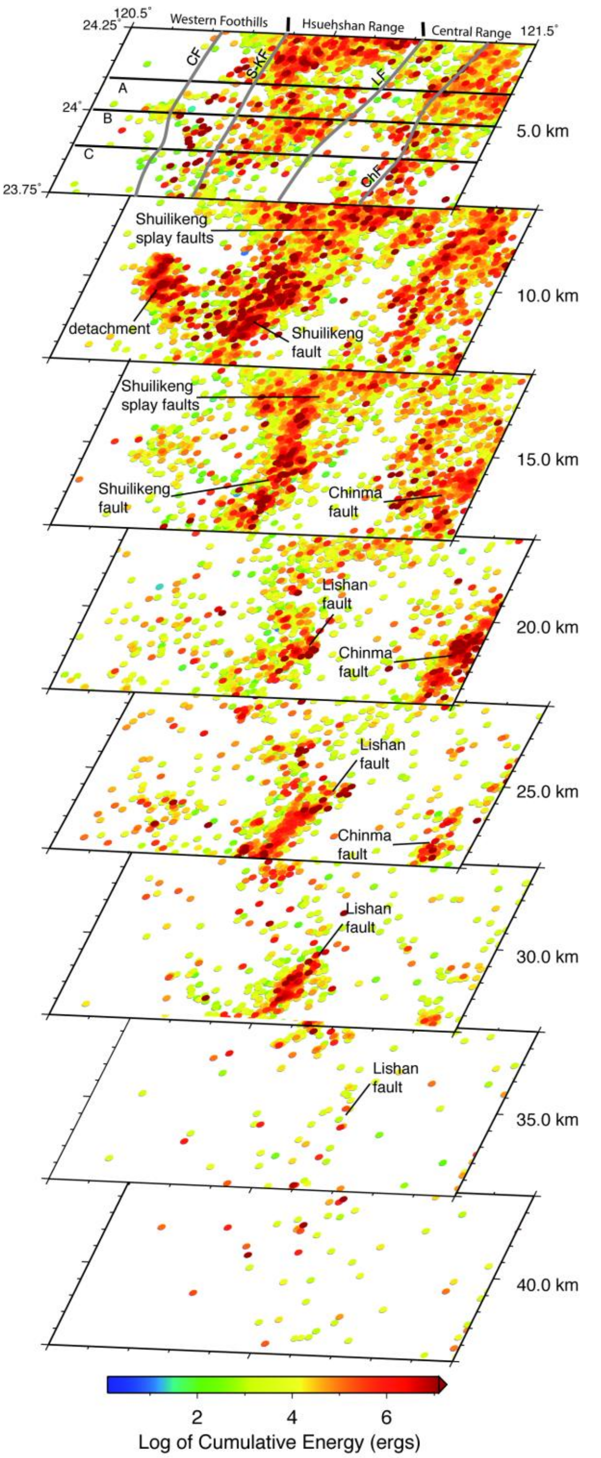


FIGURE 2. *Seismic energy release depth slices for the study area. Note the coincidence of the linear highs which are interpreted to be related to the basal detachment, the Shuilikeng and Lishan faults.*

The cumulative seismic energy release data corroborates the previous interpretations of a detachment at about 10 km depth beneath the Western Foothills, but it also suggests that this detachment does not continue eastward at this shallow level beneath the Hsuehshan and Central ranges. Instead, the Western Foothills detachment appears to ramp steeply down into the lower crust beneath the Hsuehshan Range where it either continues eastward at this deep level, or is truncated by the Lishan fault. Recently, modeling approaches have suggested that the basal detachment beneath the Hsuehshan and Central ranges is steeply dipping and located somewhere in the middle to lower crust. It is not possible to resolve this with the data set presented here, however, since the cumulative seismic energy release beneath the western part of the Central Range is too low to allow faults to be illuminated and a structural linkage to be established between it and the structure of the Hsuehshan Range.

We suggest that a model in which the Western Foothills and Hsuehshan Range is a zone of transpression with a structural architecture similar to that of a crustal-scale positive flower structure better fits the available data than the shallow through-going detachment model. In this transpression model, there is a suite of linked, active faults whose kinematics range from oblique thrusting through to strike-slip and extensional faulting, all of which respond to the same regional geodynamic stress field. The Western Foothills detachment ramps down into the lower crust along the western flank of the Hsuehshan Range and is truncated by the Lishan fault. This implies that there is no, or very limited material transfer across the Lishan fault and therefore no structural linkage in the form of a fault between the Hsuehshan and Central ranges. The western part of the Central Range is, therefore, acting as a steeply west-dipping backstop to the transpressional thrust belt that is developing in the Hsuehshan Range and Western Foothills. With the current available data sets it is not possible to resolve what is happening at depth in the Central Range, although the east-dipping Chinma Tunnel fault is clearly active and important.

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